5. Other Gases: Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride

Overview

Total U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990-2000

Estimated 2000 Emissions (Million Metric Tons Carbon Equivalent)	46.8
Change Compared to 1999 (Million Metric Tons Carbon Equivalent)	2.0
Change from 1999 *(Percent)*	*4.5%*
Change Compared to 1990 (Million Metric Tons Carbon Equivalent)	17.1
Change from 1990 *(Percent)*	*57.8%*

In addition to the three principal gases (carbon dioxide, methane, and nitrous oxide), there are other gases that account for 2.5 percent of U.S. greenhouse gas emissions when weighted by global warming potential (GWP) (see box on page 58). These gases are engineered chemicals that occur on a very limited basis in nature.[75] Although they are more potent greenhouse gases and tend to have comparatively high GWPs, they are emitted in such small quantities that their overall impact is currently small.

The guidelines of the Intergovernmental Panel on Climate Change (IPCC) define three classes of these gases that "count" for emissions estimation: hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). This chapter describes emissions sources and gives emissions estimates for HFCs, PFCs, and SF_6.

HFCs, PFCs, and SF_6 are emitted in small quantities, but they have disproportionate effects because of their large GWPs. PFCs and SF_6 have particularly high GWPs because of their scarcity in the atmosphere and long atmospheric lifetimes. SF_6 is the most potent of the greenhouse gases, with a GWP of 22,200. PFCs have GWPs in the range of 7,000 to 9,000. HFC-23 is the most potent of the HFCs, with a GWP of 12,000.[76]

Table 29 summarizes U.S. emissions of HFCs, PFCs, and SF_6 from 1990 to 2000, and Table 30 shows the corresponding emissions in million metric tons carbon equivalent. The U.S. Environmental Protection Agency (EPA) estimates total emissions of HFCs, PFCs, and SF_6 in 2000 at 46.8 million metric tons carbon equivalent—a 4.5-percent increase over 1999 emissions and a 57.8-percent increase over 1990 emissions.[77]

In summary, emissions of HFCs and PFCs are rising, and new data for SF_6 show a decline. In the case of HFCs, the rise in emissions reflects the use of HFCs as replacements for CFCs, whose use is being phased out under the Montreal Protocol because they damage the Earth's ozone layer. CFCs had been widely used as refrigerants, aerosol propellants, and foam blowing agents for many years, but with CFC production virtually ceasing by 1996, HFCs have been introduced into the market to fill the void in many key applications. The trend in HFC emissions is expected to accelerate in the next decade as HCFCs used as interim substitutes for CFCs are also phased out under the provisions of the Copenhagen Amendments to the Montreal Protocol.

Emissions of PFCs and perfluoropolyethers (PFPEs) have also been rising since 1990 (although not as rapidly as HFC emissions), mainly because of the recent commercial introduction of new PFCs and PFPEs both as CFC substitutes and for use in various applications in the semiconductor manufacturing industry. New data for SF_6 show an overall decline in emissions, 41.4 percent since 1990, as opposed to previous years' estimations. The change is the result of lower estimates of emissions from electrical transmissions and distribution.[78]

[75]See Chapter 1, Table 1. Naturally occurring (pre-industrial) emissions of perfluoromethane (CF_4) were 40 parts per trillion. Their concentration had doubled by 1998.

[76]Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001).

[77]U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa/gov/globalwarming/ (preliminary extimates, 2001). Note that EIA calculates emissions in carbon-equivalent units using the GWP values published by the IPCC in 2001 in its Third Assessment Report, whereas the EPA uses the GWP values from the IPCC's 1996 Second Assessment Report (see box on page 58).

[78]U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1999*, EPA-236-R-01-001 (Washington, DC, April 2001), web site www.epa.gov/globalwarming/publications/emissions/us2001/index.html.

The emissions estimates in Table 29 are taken from data supplied by the EPA's Office of Air and Radiation.[79] The estimates in Table 30 are based on data provided by the EPA's Office of Air and Radiation in units of native gas, which were converted to carbon-equivalent units by EIA, using GWP values from the IPCC's 2001 Third Assessment Report (see box on page 58). The 2000 preliminary estimates are advance estimates developed by the EPA and provided to EIA. They include some relatively minor revisions to the historical emissions estimates for HFCs, based on recent runs of the EPA's Vintaging Model, as well as significant revisions to historical emissions estimates for SF_6 based on new data for SF_6 emissions from electrical equipment (see boxes on page 60 and page 61). The revisions to the historical estimates are reflected in the emissions estimates presented in this chapter.

IPCC Calculates New Global Warming Potentials in 2001

Global warming potentials (GWPs) provide a means of comparing the abilities of different greenhouse gases to trap heat in the atmosphere. The GWP index converts emissions of various gases into a common measure, described as the ratio of the radiative forcing that would result from the emissions of one kilogram of a greenhouse gas to that from emissions of one kilogram of carbon dioxide (CO_2) over a period of time.[a]

In 2001, the Intergovernmental Panel on Climate Change (IPCC) Working Group I released its Third Assessment Report, *Climate Change 2001: The Scientific Basis*. Table 6.7 in the IPCC report gives revised GWPs for a number of the "other gases" included in this chapter.[b] In the table below, the revised GWPs are compared with those published in 1996 in the IPCC's Second Assessment Report, *Climate Change 1995: The Science of Climate Change*.[c]

The 2001 direct GWPs are based on an improved calculation of CO_2 radiative forcing and new values for the radiative forcing and lifetimes of a number of halocarbons.[d] One significant revision, drawn from a 1999 report by the World Meteorological Organization, *Scientific Assessment of Ozone Depletion*, is the radiative efficiency (per kilogram) of CO_2, updated to a value that is 12 percent lower than the IPCC's 1995 estimated value, at 0.01548 Wm^{-2}/ppmv (watts per square meter per part per million by volume).[d] Another significant revision is the updating of several radiative efficiencies (per kilogram), most notably, that of CFC-11. The radiative forcing estimates for halocarbon replacement gases, which are scaled relative to that of CFC-11 when their GWPs are calculated, are also affected by this change.[e]

Comparison of 1996 and 2001 IPCC Values for the Global Warming Potentials (GWPs) of "Other Gases"

Gas	1996 IPCC GWP	2001 IPCC GWP
HFC-23	11,700	12,000
HFC-125	2,800	3,400
HFC-134a	1,300	1,300
HFC-143a	3,800	4,300
HFC-152a	140	120
HFC-227ea	2,900	3,500
HFC-236fa	6,300	9,400
Perfluoromethane (CF_4)	6,500	5,700
Perfluoroethane (C_2F_6)	9,200	11,900
Sulfur Hexafluoride (SF_6)	23,900	22,200

[a]The GWPs shown here are based on a time horizon of 100 years.
[b]Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), pp. 388-389.
[c]Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), p. 121.
[d]*Climate Change 2001*, p. 386.
[e]*Climate Change 2001*, p. 387.

[79]U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov/globalwarming/ (preliminary estimates, October 2001).

Hydrofluorocarbons (HFCs)

U.S. Emissions of Hydrofluorocarbons, 1990-2000

Estimated 2000 Emissions (Million Metric Tons Carbon Equivalent)	28.1
Change Compared to 1999 (Million Metric Tons Carbon Equivalent)	2.2
Change from 1999 *(Percent)*	*8.3%*
Change Compared to 1990 (Million Metric Tons Carbon Equivalent)	18.1
Change from 1990 *(Percent)*	*181.4%*

HFCs are compounds containing carbon, hydrogen, and fluorine. They do not destroy ozone. The market for HFCs is expanding as CFCs are being phased out. Since 1990, HFC emissions have accounted for a growing share (almost 70 percent in 2000) of total carbon-equivalent emissions of HFCs, PFCs, and SF_6 combined. The EPA estimates U.S. emissions of all HFCs in 2000 at 28.1 million metric tons carbon equivalent, an 8.3-percent increase from 1999 emissions and a 181.4-percent increase from 1990.[80]

Trifluoromethane (HFC-23)

Although emissions of HFC-23 are relatively small, its high GWP (12,000)[81] gives it a substantial direct effect. HFC-23 is created as a byproduct in the production of HCFC-22 and is generally vented to the atmosphere.

The EPA estimates 2000 HFC-23 emissions at 2,546 metric tons of gas.[82] Annual emissions have fluctuated since 1990, reaching a low point in 1995 at 2,310 metric tons and peaking at 3,432 metric tons in 1998 (Table 29). The estimate for 2000 is 15 percent lower than the estimate of 1990 emissions. Consumption of HCFC-22 continues to grow, although at a slower rate than in past years. It continues to dominate the refrigerant market for stationary refrigeration and air conditioning (including chillers, room air conditioners, and dehumidifiers).[83] In addition, HCFC-22 is manufactured as a feedstock for production of polytetrafluoroethylene (PTFE) and other chemicals. The EPA administers a voluntary program with HCFC-22 producers to reduce HFC-23 emissions, which may help to offset the rising demand for HCFC-22 in the short term. In the long term, domestic production of HCFC-22 for use as a refrigerant will be phased out by 2010 under the U.S. Clean Air Act, pursuant to U.S. agreements under the Copenhagen Amendments to the Montreal Protocol, although its production for use as a feedstock will be allowed to continue indefinitely.[84]

1,2,2,2-Tetrafluoroethane (HFC-134a)

HFC-134a, with a GWP of 1,300,[85] has been the industry standard for replacing CFCs in automotive air conditioners since 1994. Emissions in 1990 were estimated at 562 metric tons of gas, but since then they have grown rapidly to 33,669 metric tons in 2000 (Table 29). The 2000 estimate is 10.8 percent higher than that for 1999.

Automobile air conditioners are subject to leakage, with sufficient refrigerant leaking (15 to 30 percent of the charge) over a 5-year period to require servicing. On its Form EIA-1605, General Motors (GM) reported total HFC-134a emissions of about 2,566 metric tons of gas in 1999.[86] GM based its estimate on an assumed annual leakage rate from mobile sources of 10 percent per year. With GM vehicles accounting for about one-third of the U.S. light-duty fleet,[87] the GM emissions estimate implies that total U.S. HFC-134a emissions from mobile air conditioners were equal to about 7,700 metric tons in 1999. Emissions from this source are expected to continue to increase in the near future, as the replacement of vehicles using CFCs proceeds at a rapid pace.

In addition to its use in all new automobiles, an automotive aftermarket for HFC-134a has been developing. Spurred by rising prices for CFC-12, 5 million cars were retrofitted for HFC-134a use in 1997.[88] This trend toward retrofitting is expected to continue, given that CFC-12 is no longer produced, remaining inventories are being depleted, and CFC-12 prices are rising.[89] Furthermore,

[80] EIA calculates emissions in carbon-equivalent units using the GWP values published by the IPCC in 2001 in its Third Assessment Report, whereas the EPA uses the GWP values from the IPCC's 1996 Second Assessment Report (see box on page 58).

[81] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001).

[82] U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov/globalwarming/ (preliminary estimates, October 2001).

[83] C. Boswell, "Hydrofluorocarbons Build with Transition Away from CFCs," *Chemical Market Reporter* (September 13, 1999).

[84] See web site www.epa.gov/ozone/index.html.

[85] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 388.

[86] Form EIA-1605 is a greenhouse gas emissions and emissions reductions reporting form, which is submitted to EIA on a voluntary basis by entities interested in creating a public record of their emissions reduction activities.

[87] American Automobile Manufacturers Association, *Motor Vehicle Facts and Figures 96* (Detroit, MI, 1999).

[88] "Fluorocarbon Outlook Turns Bullish," *Chemical Market Reporter* (May 25, 1998).

[89] J. Ouellette, "Fluorocarbon Market Is Poised To Grow," *Chemical Market Reporter* (June 19, 2000).

many of the air conditioners in mid-1990s models (which were among the first automobiles to use HFC-134a) are now due to be serviced. In 1999, a spokesperson for Elf Atochem North America estimated the U.S. aftermarket for HFC-134a at 45 to 50 million pounds, or roughly 35 percent of total annual demand. He believed that, as the market for HFC-134a matures, the aftermarket will eventually be about twice the size of the original equipment market.[90] The automotive aftermarket is already responsible for much of the growth in current HFC-134a demand.[91]

HFC-134a is also used in refrigerant blends (e.g. R-404) in most new refrigerators built in the U. S. and in commercial chillers, but leakage from these sources is much less than from automotive air conditioners. Leakage occurs primarily during servicing of the units rather than during normal operation. Short-term uses of HFC-134a, on the other hand, are becoming an important source of emissions. Such uses include aerosols and open-cell foam blowing, which are denoted as short term because most of the HFC-134a used will be emitted to the atmosphere within a short period of time.

EPA Revises Emissions Estimation Methodology

The primary source for the emission estimates presented in this chapter is data obtained from the U.S. Environmental Protection Agency (EPA), Office of Air and Radiation, which also prepares an annual inventory of greenhouse gas emissions.[a] The data supporting the EPA inventory for 2001, which includes emissions estimates through 2000, incorporates a number of revisions to the estimates of HFC, PFC, and SF_6 emissions before 1999. Those changes are reflected in the estimates presented in this chapter.

The changes to the historical emission estimates are the result of revisions to the data and estimation methodologies used by the EPA:

- In 1999, the EPA launched its Voluntary SF_6 Emissions Reduction Partnership to reduce emissions of SF_6 from equipment used to transmit and distribute electricity, such as high voltage circuit breakers, substations, transformers, and transmissions lines. Three new pieces of information were received under the EPA's voluntary program: (1) actual 1999 emissions estimates for electric power systems from participants in the program, (2) analysis of the likely relationship between the emissions estimates provided by the program participants and total emissions from U.S. electric power systems, and (3) information on world sales of SF_6 to electric power systems during the 1990s.[b]
- Estimates of SF_6 emissions from the magnesium industry were also revised on the basis of new information provided by the Voluntary SF_6 Emissions Reduction Partnership, which includes 100 percent of U.S. magnesium primary production and approximately 70 percent of magnesium casting. The U.S. Geological Survey provides U.S. magnesium metal production (primary and secondary) and consumption data for 1993-1999. These revisions and others combined to result in a total decrease in SF_6 emissions of 1,662 metric tons of gas (4.8 percent) from 1990 to 1999.[c]
- The Voluntary Aluminum Industrial Partnership Program and EPA's Global Programs Division provided data to revise the estimation methods for emissions from aluminum production.[d]
- The methodology for estimating emissions from semiconductor manufacturing has been updated to include production data for 1990-1994 and data reported directly by semiconductor manufacturers for other years. The revisions resulted in an average decrease in annual HFC, PFC, and SF_6 emissions from semiconductor manufacturing of 0.1 million metric tons carbon equivalent (5 percent) for 1990-1998.[e]
- For ozone-depleting substance (ODS) substitutes, revisions to chemical substitution trends and new information from industry representatives have led to revised assumptions for the EPA's Vintaging Model, in particular related to cleaning solvents, stationary refrigeration, and fire extinguishing equipment. The revisions resulted in an average decrease in annual emissions of HFCs, PFCs and SF_6 from their use as ODS substitutes of 2.1 million metric tons carbon equivalent (19 percent) for 1994-1998.[d]

[a]U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1999*, EPA-236-R-01-001 (Washington, DC, April 2001), web site www.epa.gov/globalwarming/publications/emissions/us2001/index.html.
[b]E-mail correspondence with U.S. Environmental Protection Agency, Office of Air and Radiation, August 2001.
[c]*Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1999*, p. 3-30.
[d]*Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1999*, p. xiv.
[e]*Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1999*, p. xix.

[90]"HFC-134a Prices Rise as Market Tightens," *Chemical Market Reporter* (March 15, 1999).
[91]J. Ouellette, "Fluorocarbon Market Is Poised To Grow," *Chemical Market Reporter* (June 19, 2000).

According to the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS), worldwide sales of HFC-134a for short-term applications jumped almost fourfold between 1994 and 1995. Sales for short-term uses leveled off at 10,500 metric tons in 1996 and then dropped to 6,500 metric tons in 1998; however, new developments in the U.S. market have reversed the downward trend, as sales of HFC-134a totaled 14,300 metric tons in 1999.[92]

In January 1999, the major marketers of tire inflaters began requiring the use of nonflammable material, creating additional demand for HFC-134a. Pennzoil was the first company to enter this new market, after removing its hydrocarbon-based canisters and reconfiguring them to use HFC-134a.[93]

For many years, the HFC-134a market was characterized by excess capacity and low prices, because the transition away from CFC-12 occurred more slowly than producers had expected.[94] In 1998 and 1999, however, the market tightened considerably, as evidenced by a series of price increases. Driven in part by a demand surge triggered by an unusually hot summer in 1999, prices nearly doubled, rising from a low of $1.50 per pound to $2.50 per pound by September 1999. For the rest of 1999 and the first half of 2000, the market stabilized, with only one minor price increase in early 2000.

A number of HFC-134a producers are undertaking modest capacity expansion projects, including Dupont, INEOSFluor (formerly ICI Klea), and Honeywell (formerly AlliedSignal). More significant additions of new capacity are likely to be needed, however, given that capacity is increasing by only 2 to 3 percent per year, while global demand is growing by 10 percent. SRI International predicts that global demand will reach 20 million pounds by 2001; and according to a representative of Elf Atochem, the market will face significant supply shortages unless more investment in new capacity is undertaken over the next several years.[95] The required capacity will presumably be built, but it is possible that the expansion in supply will lag behind the growth in demand. Anticipating and planning for this growth has proven to be a difficult challenge for producers, who must manage as best as possible an unprecedented transition from an established product (CFC-12) that is now under a global ban, to a new product (HFC-134a). In the long term, consumption and emissions of HFC-134a will continue to rise rapidly, although it is possible that capacity constraints may act as a brake on consumption in the near term.

1,1-Difluoroethane (HFC-152a)

As a non-ozone-depleting substance with a GWP of 120,[96] HFC-152a is an attractive potential replacement for CFCs. It can be used as a blowing agent, an

The EPA Vintaging Model: Estimation Methods and Uncertainty

The U.S. Environmental Protection Agency (EPA) uses a detailed Vintaging Model for equipment and products containing ozone-depleting substances (ODS) to estimate actual versus potential emissions of various ODS substitutes, including hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs). The model estimates the quantities of ODS-containing equipment and products sold each year, and the amounts of chemicals required for their manufacture and/or maintenance over time. Emissions from more than 40 different end uses are estimated by applying annual leak rates and release profiles, which account for the lag in emissions from equipment as they leak over time.

For most products (refrigerators, air conditioners, fire extinguishers, etc.), emissions calculations are split into two categories: emissions during equipment lifetime, which arise from annual leakage and service losses plus emissions from manufacture; and disposal emissions, which occur when the equipment is discarded. By aggregating the data over different end uses, the model produces estimates of annual use and emissions of each compound.[a] The EPA is consistently making improvements to the model to use more accurate data from the industries and to reduce uncertainty.

[a]U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gases and Sinks 1990-1999*, EPA-236-R-01-001 (Washington, DC, April 2001), Annex I, web site www.epa.gov/globalwarming/publications/emissions/us2001/index.html.

[92]Alternative Fluorocarbons Environmental Acceptability Study, *Production, Sales and Atmospheric Release of Fluorocarbons Through 1999*, web site www.afeas.org/prodsales_download.html.
[93]J. Ouellette, "Fluorocarbon Market Is Poised To Grow," *Chemical Market Reporter* (June 19, 2000).
[94]C. Boswell, "Hydrofluorocarbons Build with Transition Away from CFCs," *Chemical Market Reporter* (September 13, 1999).
[95]J. Ouellette, "Fluorocarbon Market Is Poised To Grow," *Chemical Market Reporter* (June 19, 2000).
[96]Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 388.

ingredient in refrigerant blends (e.g., in R-500), and in fluoropolymer manufacturing applications. There are no HFC-152a emissions associated with the latter application, because the HFC-152a is consumed in the manufacturing process. In 1996, 5 million pounds of HFC-152a was consumed in fluoropolymer manufacturing.[97] HFC-152a is also compatible with the components used in aerosol products. Unlike CFCs, however, HFC-152a is flammable.

Only one U.S. company (DuPont) produces HFC-152a, using the trade name Dymel-152a. DuPont probably was producing HFC-152a at nearly full capacity in 1994, corresponding to production of about 8,000 metric tons. In 1995, the company reported having doubled its production capacity from 1992 levels to 15,875 metric tons.[98] The company reported on its 1999 Form EIA-1605 that 1994 HFC-152a emissions peaked at 200 metric tons. By 1998, however, DuPont's reported emissions had dropped to 40 metric tons. The EPA estimates HFC-152a emissions in 2000 at 1,552 metric tons of gas, an increase of 3.5 percent over the 1990 estimate.[99]

Other HFCs

Other hydrofluorocarbons with considerable radiative forcing potential include HFC-125 (C_2HF_5), HFC-143a ($C_2H_3F_3$), HFC-227ea (C_3HF_7), HFC-236fa ($C_3H_2F_6$), and HFC-4310 ($C_5H_2F_{10}$), with 100-year GWPs of 3,400,4,300, 3,500, 9,400, and 1500 respectively.[100] The EPA estimates total emissions of this group of "other HFCs" at 4.4 million metric tons carbon equivalent in 2000, representing 9.5 percent of all emissions of HFCs, PFCs, and SF_6 reported (Table 30).[101] Emissions of these HFCs are small but growing rapidly, as they continue to find applications as substitutes for CFCs. Emissions of "other HFCs" have increased by 10.5 percent since 1999.

HFC-125 is used in the blend R-410A, which is designed to replace HCFC-22 as the refrigerant of choice for stationary refrigeration and air conditioning applications. Some manufacturers have already introduced air conditioners that use R-410A, but as yet the product has captured a small percentage of the market. As the phaseout of HCFC-22 begins to gain momentum, Honeywell expects a rapid increase in the demand for R-410A.[102] The EPA estimates emissions of HFC-125 at 236 metric tons of gas in 1992, increasing to 1,561 metric tons in 2000 (Table 29). The estimate for 2000 is 21.1 percent higher than the estimate for 1999.[103]

HFC-143a is a halocarbon used in refrigeration and air conditioning, in blends such as R-404A, R-406A, R-408A, and R-507A. HFC-143a is used as a substitute because it contains neither chlorine or bromine and will not emit ozone-depleting halogen radicals into the stratosphere. Like other halocarbons, HFC-143a does make a positive contribution to atmospheric warming; however its GWP is lower than those of the gases it replaces, such as CFC-11 or those in the blend R-502. The EPA estimates 1993 emissions of for HFC-143a at 16 metric tons of gas, increasing to 903 metric tons in 2000. The 2000 estimate is 33.6 percent higher than the estimate for 1999.[104]

HFC-236fa is also used as a refrigerant, in particular by the U.S. Navy for shipboard applications.[105] The EPA estimates 1997 emissions of HFC-236fa at 14 metric tons of gas, increasing to 297 metric tons in 2000. The estimate for 2000 is 39.4 percent higher than the estimate for 1999.[106] Other HFCs and HFC blends are also likely to gain market share as a result of the phaseout, because no single product is suited for all applications. For example, each potential replacement product has an optimal operating temperature range; hence, the refrigerant best suited for use in ice cream freezers will differ from the best choice for milk coolers.[107]

In addition to replacing HCFC-22 in stationary air conditioning and refrigeration applications, other HFCs are expected to gain new markets as foam blowing agents. CFCs have already been phased out of this market, having been replaced by HCFCs (primarily HCFC-141b).

[97] C. Boswell, "Hydrofluorocarbons Build with Transition Away from CFCs," *Chemical Market Reporter* (September 13, 1999).
[98] "DuPont Set To Expand Markets for Ozone-Safe HFC-152a Product," *Ozone Depletion Online Today* (Alexandria, VA, June 9, 1995).
[99] U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov/globalwarming/ (preliminary estimates, October 2001).
[100] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 388.
[101] U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov/globalwarming/ (preliminary estimates, October 2001). EIA calculates emissions in carbon-equivalent units using the GWP values published by the IPCC in 2001 in its Third Assessment Report, whereas the EPA uses the GWP values from the IPCC's 1996 Second Assessment Report (see box on page 58).
[102] J. Ouellette, "Fluorocarbon Market Is Poised To Grow," *Chemical Market Reporter* (June 19, 2000).
[103] U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov/globalwarming/ (preliminary estimates, October 2001).
[104] U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov/globalwarming/ (preliminary estimates, October 2001).
[105] E-mail correspondence with the Office of Policy, U.S. Department of Energy, October 18, 2000.
[106] U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov/globalwarming/ (preliminary estimates, October 2001).
[107] C. Boswell, "Hydrofluorocarbons Build with Transition Away from CFCs," *Chemical Market Reporter* (September 13, 1999).

Among the potential replacements, HFC-245fa appears to be the strongest contender.[108]

Honeywell is building a world-scale plant in Louisiana for the production of HFC-245fa which will become fully operational by July 2002. Semi-commercial quantities of the product will be available from the plant in the third quarter of 2000.[109] Honeywell is also developing blends that combine HFC-245fa with other materials to enhance its cost/performance ratio. To date, however, the foam blowing industry has failed to signal a clear preference for HFC-245fa or other alternatives. Instead, it continues to rely primarily on HCFC-141b while waiting to see which of the possible replacement candidates emerges as the preferred alternative.[110] For some applications, non-fluorochemical alternatives (e.g., hydrocarbons) have been identified.[111]

Perfluorocarbons (PFCs)

U.S. Emissions of Perfluorocarbons, 1990-2000

Estimated 2000 Emissions (Million Metric Tons Carbon Equivalent)	8.7
Change Compared to 1999 (Million Metric Tons Carbon Equivalent)	-0.34
Change from 1999 *(Percent)*	*-3.7%*
Change Compared to 1990 (Million Metric Tons Carbon Equivalent)	-1.5
Change from 1990 *(Percent)*	*-14.4%*

*Less than 0.05 million metric tons.

PFCs are compounds composed of carbon and fluorine. PFC emissions are not regulated, although their high GWPs (5,700 for perfluoromethane [CF_4] and 11,900 for perfluoroethane [C_2F_6])[112] have drawn attention. PFCs are also characterized by long atmospheric lifetimes (up to 50,000 years); hence, unlike HFCs, they are essentially permanent additions to the atmosphere. The EPA estimates 2000 emissions of PFCs at 8.7 million metric tons carbon equivalent, slightly lower than 1999 emissions and 14.4 percent lower than 1990 emissions (Table 30).[113]

The principal quantifiable source of PFCs is as a byproduct of aluminum smelting created by the frequency and duration of anode effects during periods of process inefficiency. The EPA estimates U.S. emissions from aluminum production at 1,096 metric tons of perfluoromethane and 90 metric tons of perfluoroethane in 2000.[114] Reductions in primary aluminum production and efficiency improvements to reduce anode effects have reduced emissions of perfluoromethane and perfluoroethane since 1990 by 55 percent and 64 percent, respectively. Many of the efficiency improvements have been achieved as a result of the EPA's Voluntary Aluminum Partnership, which was launched in 1995. According to the U.S. Geological Survey, strong demand for aluminum in manufacturing passenger cars and light trucks is expected to increase overall consumption;[115] however, domestic aluminum production declined in 2000 due to high energy costs and subsequent smelter production cutbacks.[116]

Another source of PFC emissions is semiconductor manufacturing. Perfluoromethane and perfluoroethane are used as etchants and cleaning agents in semiconductor manufacturing. The United States consumed an estimated 800 tons of perfluoroethane and perfluoromethane in 1995.[117] For 2000, the EPA estimates emissions of perfluoromethane and perfluoroethane from semiconductor manufacturing at 286 metric tons and 431 metric tons of gas, respectively.[118] Both estimates are 4.6 percent lower than the corresponding estimates for 1999 emissions. It is difficult to assess trends in PFC emissions from the semiconductor industry. On the one hand, the continued rapid expansion of the worldwide semiconductor market may lead to increased PFC use and emissions. On the other hand, industry efforts to

[108]C. Boswell, "Hydrofluorocarbons Build with Transition Away from CFCs," *Chemical Market Reporter* (September 13, 1999).

[109]Honeywell, "Honeywell Set To Commercialize Non-Ozone-Depleting HFC-245fa Blowing Agent Product," News Release (March 27, 2000), web site www.genetron.com/applications/blowingagents/pdfs/blowing_agents_march27_2000.pdf.

[110]C. Boswell, "Hydrofluorocarbons Build with Transition Away from CFCs," *Chemical Market Reporter* (September 13, 1999).

[111]J. Ouellette, "Fluorocarbon Market Is Poised To Grow," *Chemical Market Reporter* (June 19, 2000).

[112]Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 389.

[113]EIA calculates emissions in carbon-equivalent units using the GWP values published by the IPCC in 2001 in its Third Assessment Report, whereas the EPA uses the GWP values from the IPCC's 1996 Second Assessment Report (see box on page 58).

[114]U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov/globalwarming/ (preliminary estimates, October 2001).

[115]U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1999*, EPA-236-R-01-001 (Washington, DC, April 2001), web site www.epa.gov/globalwarming/publications/emissions/us2001/index.html.

[116]U.S. Geological Survey, Mineral Commodity Summaries (January 2001), web site http://minerals.usgs.gov/minerals/pubs/commodity/aluminum/050301.pdf.

[117]"PFCs Can Be Recycled with New Technology," American Institute of Chemical Engineers, Press Release (March 12, 1997).

[118]U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov/globalwarming/ (preliminary estimates, October 2001).

curb emissions may help to offset these market forces to some extent.

A number of semiconductor manufacturing firms have joined an EPA program to reduce PFC emissions voluntarily.[119] In 1999, the World Semiconductor Council, comprising manufacturers from Europe, the United States, Japan, and Korea, voluntarily committed to reduce emissions of PFCs by 10 percent from 1995 levels by 2010. In addition, a number of PFC distributors are developing PFC emissions control equipment.[120] Abatement and other control options are commercially available and substitute chemicals that result in reduced emissions are being adopted.[121]

A variety of other perfluorinated compounds are used in the semiconductor industry, including C_3F_8 (which is manufactured by 3M and has a GWP of 8,600), C_4F_{10} (GWP 8,600), C_6F_{14} (GWP 9,000), NF_3 (manufactured by Air Products), and CHF_3.[122]

Sulfur Hexafluoride (SF_6)

U.S. Emissions of Sulfur Hexafluoride, 1990-2000

Estimated 2000 Emissions (Million Metric Tons Carbon Equivalent)	5.5
Change Compared to 1999 (Million Metric Tons Carbon Equivalent)	-0.25
Change from 1999 *(Percent)*	*-4.3%*
Change Compared to 1990 (Million Metric Tons Carbon Equivalent)	-3.9
Change from 1990 *(Percent)*	*-41.4%*

Sulfur hexafluoride (SF_6) is used primarily as a dielectric in electrical transmission and distribution systems, specifically as an insulator for circuit breakers, switch gear, and other electrical equipment. In addition, its extremely low atmospheric concentration makes it useful as an atmospheric tracer gas for a variety of experimental purposes. Another important use of SF_6 is as a cover gas during magnesium production and processing to prevent excessive oxidation of molten magnesium in the presence of air. Other sources of SF_6 emissions include fugitive emissions from certain semiconductor manufacturing processes, and the occasional use of SF_6 in experimental and specialized casting operations by the aluminum industry as a cover gas or a fluxing and degassing agent (using an industry-wide estimated 230,000 kilograms of SF_6 per year in the United States and Canada).[123] However, the latter estimate is highly uncertain and so slight that it is not included in models for SF_6 emissions.

SF_6 has a very high GWP of 22,200,[124] but it is not emitted in large quantities. Recent improvements to EPA's estimation methods have changed previous estimates of SF_6 emissions (see box on page 60). Based on new information, mainly from the Voluntary SF_6 Emission Reduction Partnerships for Electric Power Systems and for the Magnesium Industry, the most recent EPA estimates show a steady decrease in U.S. SF_6 emissions, from a peak of 1,672 metric tons of gas in 1993 to 909 metric tons in 2000, representing an overall decrease of 41.4 percent since 1990.[125] While there is a growing demand for magnesium products from U.S. casting companies to meet the requirements of changing automobile designs, no substantial expansion in the U.S. magnesium production industry is expected. Foreign magnesium producers are expected to supply the growing U.S. demand.[126]

Ozone-Depleting Substances and Criteria Pollutants

In previous years, this chapter included emissions estimates and accompanying discussions for a variety of gases that have ambiguous effects on climate, including ozone-depleting substances—chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and bromofluorocarbons (halons). This chapter also covered the criteria pollutants—carbon monoxide (CO), nitrogen oxides (NO_x), and nonmethane volatile organic compounds (NMVOCs)—which have indirect effects on

[119]"Environmental Protection Drives Emissions Reduction Effort," *Electronic Design* (December 1, 1997).

[120]"EPA Launches PFC Reduction Program," *Chemical Week* (July 31, 1996). Without emissions control efforts, PFC emissions would be expected to rise as the use of PFCs in the semiconductor industry increases.

[121]E-mail correspondence with U.S. Environmental Protection Agency, Global Programs Division, October 18, 2000.

[122]Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 389.

[123]U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1999*, EPA-236-R-01-001 (Washington, DC, April 2001), p. 3-23, web site www.epa.gov/globalwarming/publications/emissions/us2001/index.html.

[124]Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 389.

[125]U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov/globalwarming/ (preliminary estimates, October 2001).

[126]U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1999*, EPA-236-R-01-001 (Washington, DC, April 2001), web site www.epa.gov/globalwarming/publications/emissions/us2001/index.html.

climate through their effects on atmospheric concentrations of greenhouse gases. Currently, emissions estimates for those gases are not included in this chapter, because the ozone-depleting substances and criteria pollutants were excluded from the Kyoto Protocol. Furthermore, production of the ozone-depleting gases is being phased out under the Montreal Protocol. Although no longer included in the main body of this report, emissions estimates for ozone-depleting substances and criteria pollutants can be found in Appendix D, "Emissions Sources Excluded."

Table 29. U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990-2000
(Thousand Metric Tons of Gas)

Gas	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Hydrofluorocarbons											
HFC-23	3.0	2.6	3.0	2.7	2.7	2.3	2.7	2.6	3.4	2.6	2.6
HFC-134a	0.6	0.6	0.6	2.9	6.4	14.4	19.0	23.5	26.9	30.4	33.7
HFC-152a	W	W	W	W	W	W	W	W	W	W	W
HFC-125	*	*	0.2	0.5	0.3	0.5	0.7	0.9	1.1	1.3	1.6
HFC-227ea	W	W	W	W	W	W	W	W	W	W	W
HFC-143a	*	*	*	*	0.1	0.1	0.2	0.3	0.5	0.7	0.9
HFC-4310mee	W	W	W	W	W	W	W	W	W	W	W
HFC-236fa	*	*	*	*	*	*	*	*	0.1	0.2	0.3
Perfluorocarbons											
CF_4	5.1	4.8	4.7	4.6	4.4	4.4	4.5	4.3	4.1	4.1	4.0
C_2F_6	0.7	0.7	0.6	0.7	0.7	0.8	0.7	0.8	0.8	0.8	0.8
C_4F_{10}	*	*	*	*	*	*	*	*	*	*	*
PFCs/PFPEs	W	W	W	W	W	W	W	W	W	W	W
Sulfur Hexafluoride	**1.6**	**1.6**	**1.5**	**1.7**	**1.6**	**1.4**	**1.4**	**1.4**	**1.1**	**1.0**	**0.9**

*Less than 50 metric tons of gas.
P = preliminary data. W = withheld to avoid disclosure of confidential data.
Note: Totals may not equal sum of components due to independent rounding.
Source: U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov/globalwarming/ (preliminary estimates, October 2001).

Table 30. U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990-2000
(Million Metric Tons Carbon Equivalent)

Gas	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Hydrofluorocarbons											
HFC-23	9.74	8.61	9.74	8.92	8.83	7.62	8.76	8.48	11.27	8.63	8.48
HFC-134a	0.20	0.20	0.22	1.02	2.26	5.12	6.75	8.34	9.54	10.78	11.94
HFC-125	*	*	0.22	0.45	0.28	0.44	0.63	0.82	1.04	1.20	1.45
HFC-143a	*	*	*	*	0.06	0.13	0.24	0.39	0.57	0.79	1.06
HFC-236fa	*	*	*	*	*	*	*	*	0.31	0.55	0.76
Total	**9.99**	**8.84**	**10.19**	**10.43**	**12.49**	**15.54**	**18.98**	**21.24**	**26.26**	**25.95**	**28.12**
Perfluorocarbons											
CF_4	7.96	7.46	7.23	7.15	6.81	6.87	6.99	6.75	6.37	6.38	6.15
C_2F_6	2.24	2.11	2.06	2.14	2.13	2.47	2.40	2.54	2.61	2.69	2.58
C_4F_{10}	*	*	*	*	*	*	*	*	*	*	*
Total	**10.20**	**9.58**	**9.29**	**9.29**	**8.95**	**9.34**	**9.39**	**9.29**	**8.98**	**9.07**	**8.73**
Other HFCs, PFCs/PFPEs	**0.05**	**0.02**	**0.01**	**0.02**	**1.06**	**2.22**	**2.59**	**3.17**	**3.54**	**4.02**	**4.44**
Sulfur Hexafluoride	**9.41**	**9.73**	**9.14**	**10.13**	**9.42**	**8.31**	**8.36**	**8.19**	**6.93**	**5.76**	**5.51**
Total Emissions	**29.65**	**28.14**	**28.62**	**29.85**	**31.92**	**35.42**	**39.32**	**41.89**	**45.72**	**44.79**	**46.80**

*Less than 50,000 metric tons carbon equivalent.
P = preliminary data.
Notes: Other HFCs, PFCs/PFPEs include HFC-152a, HFC-227ea, HFC-4310mee, and a variety of PFCs and perfluoropolyethers (PFPEs). They are grouped together to protect confidential data. Totals may not equal sum of components due to independent rounding.
Source: U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov/globalwarming/ (preliminary estimates, October 2001). Note that EIA calculates emissions in carbon-equivalent units using the GWP values published by the IPCC in 2001 in its Third Assessment Report, whereas the EPA uses the GWP values from the IPCC's 1996 Second Assessment Report (see box on page 58).